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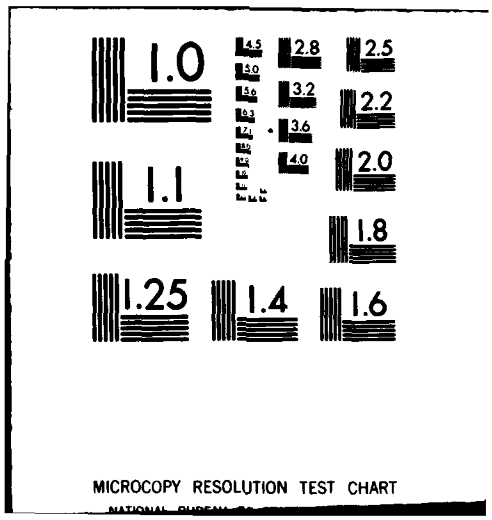
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AN INVESTIGATION OF THE IMPACT BEHAVIOR OF VACUUM-FORMED TETRACORE

I. E. Figge, Sr.

March 1980

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Prepared for

APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

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Vacuum-formed cellulose butyl-acetate Tetracore specimens were subjected to flatwise compression, torsion, and three-point bending tests to compare the results with a three-dimensional finite element computer program which was specifically developed to analyze Tetracore structures. Results indicate that the computer program is capable of accurately predicting the deflection of Tetracore panels with face sheets. In addition, low velocity impact tests at 10 and 14 fps were conducted to determine the energy-absorbing characteristics. The results indicate that the basic geometry of Tetracore provides an inherent energy-absorbing capability due to the accordian-type failure mode if ductile materials are used.

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INTRODUCTION

Tetracore, a three-dimensional structure, is being developed and evaluated by the Applied Technology Laboratory for potential application to Army aircraft. Primary emphasis has been directed toward fabrication, structural test, and analysis of filament-wound Tetracore elements, including the development of a three-dimensional elastoplastic finite element math model.[1] Initial testing of filament-wound Tetracore elements in flatwise compression indicated a load-deflection curve which demonstrated desirable crash-impact, energy-absorbing characteristics.[2]

To provide a better understanding of the behavior of Tetracore, an experimental program was undertaken to check the agreement with the math model and to investigate the crash-impact, energy-absorbing characteristics. Vacuum-formed/bonded cellulose butylacetate (ABC) plastic Tetracore specimens were selected for evaluation instead of filament-wound specimens, since the properties of stacked filamentary roving used in forming filament-wound Tetracore elements have not been thoroughly established. It was recognized that ABC is not normally considered a structural material; however, due to the high structural efficiency of Tetracore, the strength/stiffness of the material was considered to be sufficient for the purpose of this investigation.

During the impact investigation, it was found that the ABC was failing in a brittle fashion and, as a result, was not providing desirable energy-absorbing characteristics. To reduce the brittle tendency, the remaining specimens were subjected to methyl ethyl ketone (MEK) fumes by suspending the specimens over MEK fluid in a closed container for various lengths of time. This technique simply provided a sufficient ductility to achieve desirable energy-absorbing characteristics without significantly affecting the elastic behavior. The chemical reactions resulting from the solvent-type fumes (long-term effects, etc.) were not investigated.

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[1] Dobyns, Alan Lee, and Jack, David C., *A Tetra-Core Stress Analysis Model*, USAAMRDL Technical Report 72-17, Eustis Directorate, US Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1972, AD 744505.

[2] Figge, I. E., *Tetra-Core: A Three Dimensional Space Structure*, Army Science Conference, West Point, New York, 16-19 June 1970.

SPECIMEN FABRICATION

The majority of the test specimens were fabricated from 0.080-inch-thick ABC. In select cases, 0.100- and 0.060-inch-thick material was used. The halves of the Tetracore elements were vacuum formed on a mold consisting of a series of male tetrahedrons (see Figure 1). Due to the geometry of the tetrahedrons (equilateral), the vacuum-forming process resulted in approximately 50 percent draw, thus producing a wall thickness of 0.040 inch for the 0.080-inch-thick material. The two halves of the Tetracore elements were then nested together such that the faces of the tetrahedrons formed continuous planes along three axes. In general, the halves of the specimens were bonded at each corner of the tetrahedron using ABC cement. In some instances, the specimens were bonded by immersing them in MEK for approximately 1 minute, causing the surface of the material to partially dissolve and thus act as its own adhesive. A typical specimen is shown in Figure 2. Aluminum face sheets of various thicknesses were bonded to either one or both sides of the completed Tetracore panel with FE-004-9 epoxy resin. A 1/4-inch hole was drilled in the center of each triangular face of one specimen to relieve internal pressure during impact loading.

For comparison, an aluminum riveted skin/stringer specimen (typical of helicopter fuselage construction) was also tested. This specimen is shown in Figure 3.

Figure 1. Male mold used to vacuum form tetrahedrons.

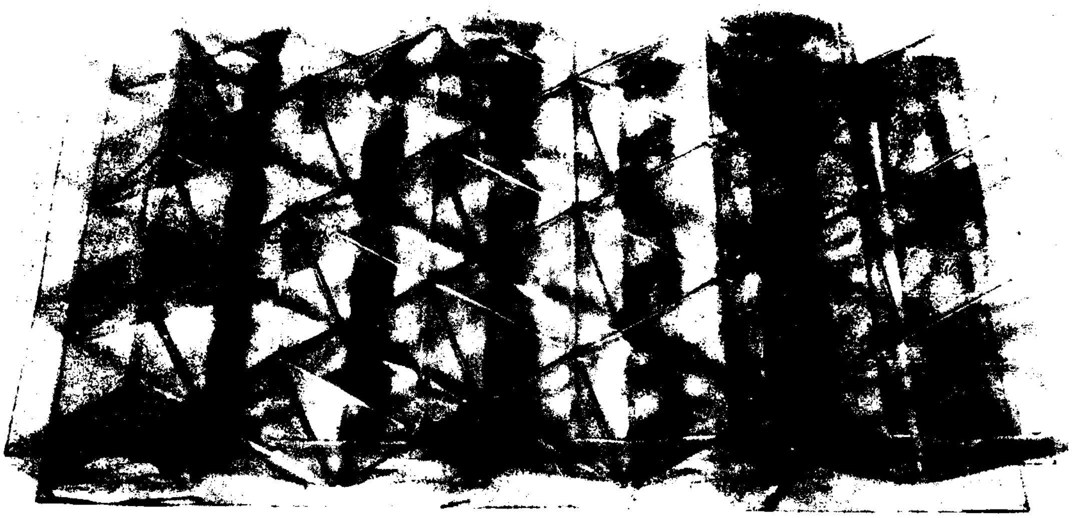

Figure 2. Assembled Tetracore specimens.

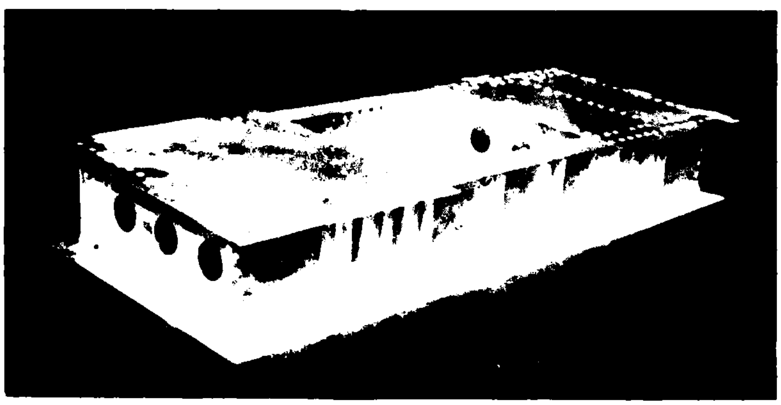

Figure 3. Aluminum skin/stringer specimen.

TESTING

A three-dimensional finite element stress analysis computer program[1] was developed to provide a tool for defining the structural behavior of Tetracore. The model uses material properties (ultimate strength, Poisson ratio, and modulus) and applied loads to determine the local stress state, deflection, and margins of safety of Tetracore elements. The primary purpose of this portion of the study was to determine the accuracy between the measured and calculated deflections, based on three-point bending tests. Flatwise compression and torsional tests were also conducted to further define the behavior of Tetracore. Low velocity impact tests were then conducted to determine the energy-absorbing characteristics of the structure.

STATIC TESTS

The bending tests were conducted with specimens having no face sheets, specimens having face sheets on one side, and specimens having face sheets on both sides. The influence of face sheets on the three-point deflection (17.5-inch total span) is shown by increases in stiffness by factors of approximately 2 and 10 for specimens with face sheets on one side and both sides, respectively, as compared to specimens without face sheets (see Figure 4). The calculated results[1] are presented in Figure 4 for two values of tensile moduli (flexure moduli not available)--200,000 psi and 250,000 psi--which bracket the extremes of the handbook values. The calculated deflections for the specimens with face sheets agree closely with the measured values. The measured deflections for specimens without face sheets fall considerably below the calculated values. This is attributed to the fact that the triangular elements in the outstanding faces (top and bottom) of the Tetracore specimen provided buckling stability to the legs of the Tetracore elements and carried some of the bending loads, thus, in effect, acting as partial face sheets.

To verify the above effect, the triangular elements were removed from first one and then both of the outer surfaces of the specimen and the three-point bending deflections were measured (Figure 5). With elements removed from one side, the deflections at 100 pounds increased from an average of 0.106 inch to 0.143 inch. With elements removed from both faces, the legs of the specimen buckled at approximately 10 pounds, which agrees closely with the calculated critical buckling load. At a 50-pound load, the deflection was 0.15 inch; the testing was terminated at this point due to this excessive deflection.

Surprisingly, the specimens with face sheets did not deflect with uniform curvature. In general, as indicated by placing a straightedge on the outer face, essentially no curvature between the reaction points and the point of load application was observed, thus resulting in a V-shaped deflection mode. The ends of the specimen overlapping the extreme reaction points curved noticeably downward as opposed to the upward curvature normally demonstrated by isotropic materials. This behavior might possibly be attributed to local deflection at the points of load application.

The flatwise static compression test results are presented in Figure 6. The results indicate yield stresses of approximately 26.8 psi and 63.5 psi for the 0.030- and 0.050-inch-thick

material, respectively. After yielding, the load dropped off slightly until the specimen crushed approximately 1.5 inches, at which time a sharp rise in load occurred.

The torsional stiffness test results are presented in Figure 7. The curve is essentially linear over the range investigated.

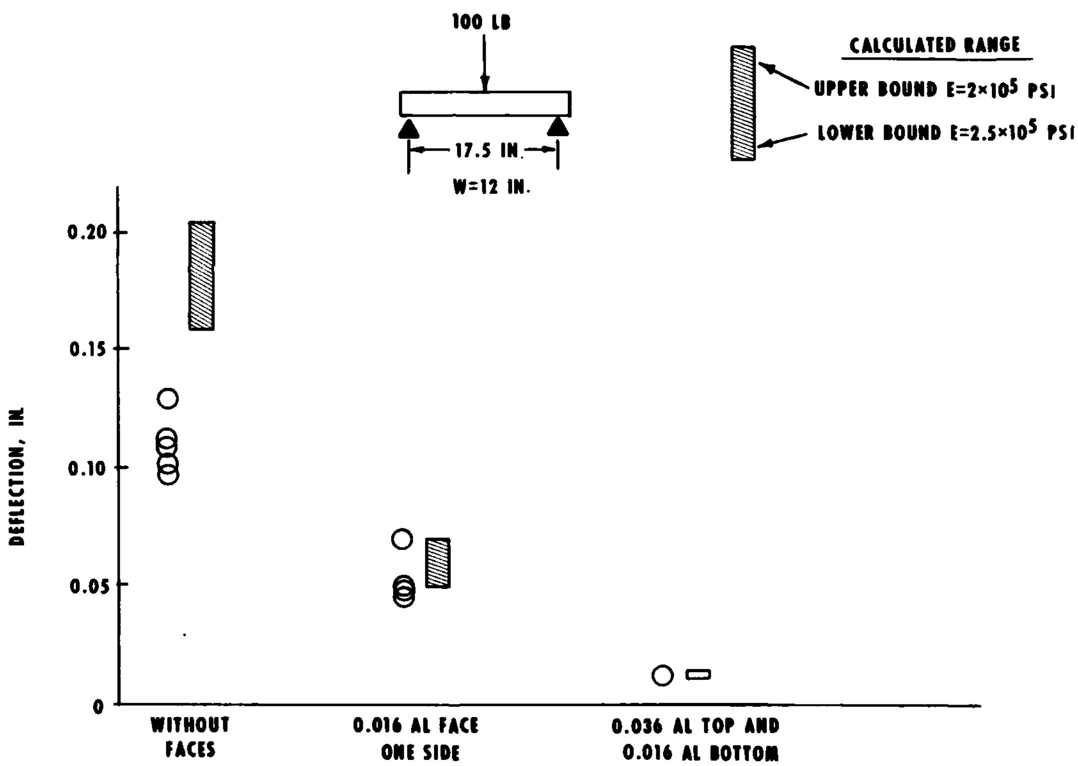

Figure 4. Effect of face sheet on three-point bending behavior.

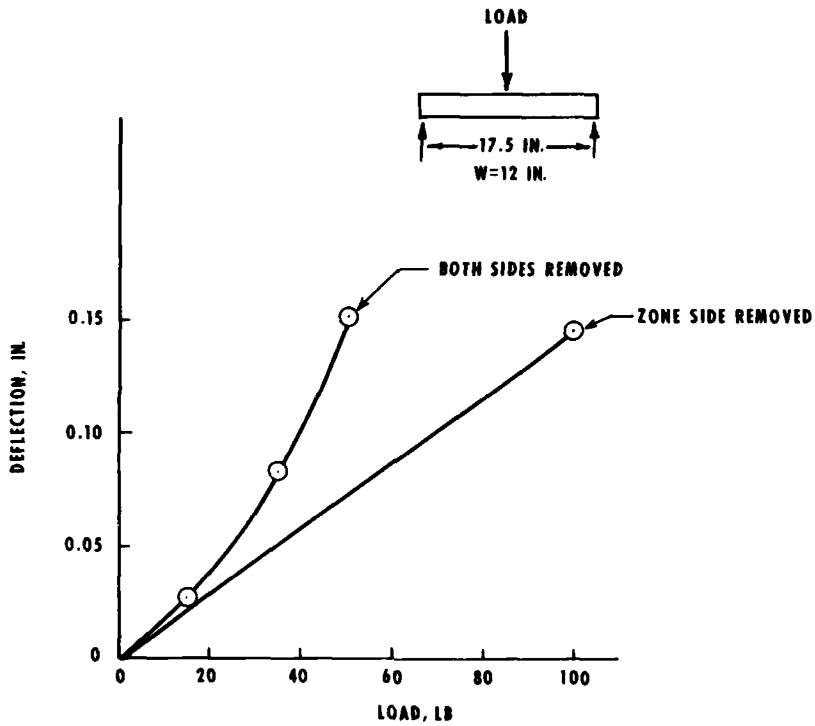

Figure 5. Effect of removing triangular face elements on three-point bending behavior.

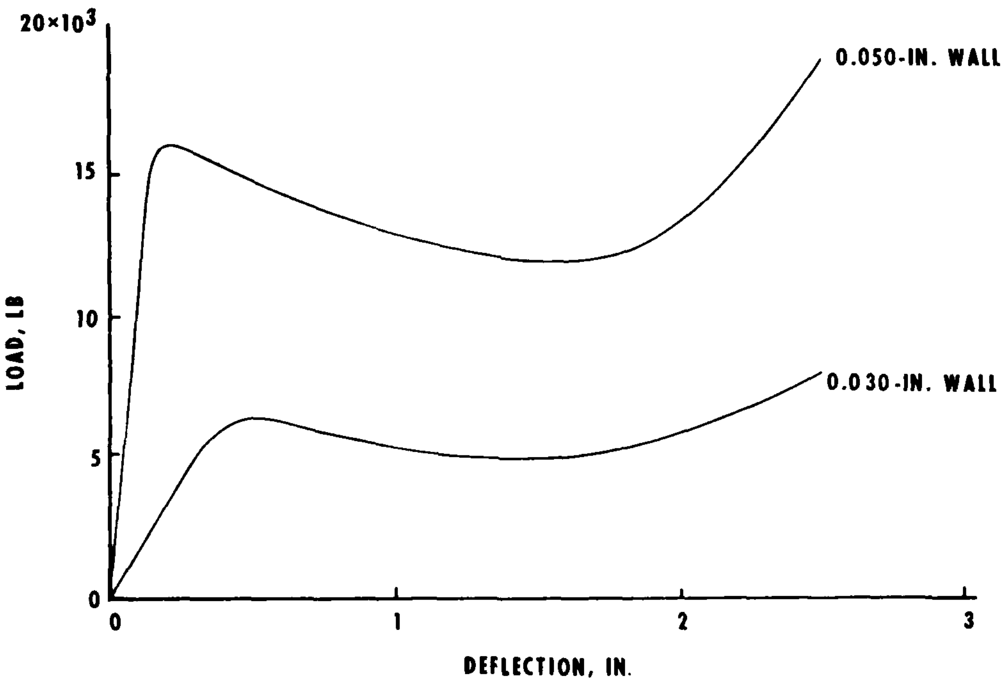

Figure 6. Effect of wall thickness on flatwise compression behavior; 2.8- by 12- by 21-inch specimen.

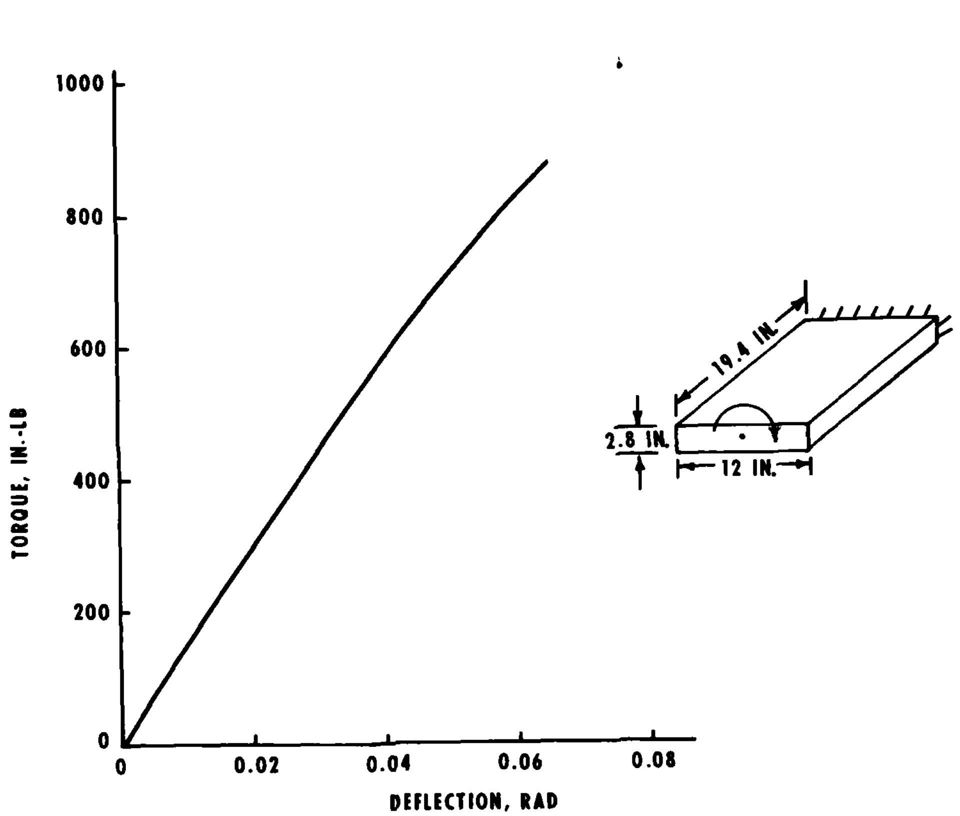

Figure 7. Torsional behavior of 0.050-inch-wall Tetracore.

IMPACT TESTS

After static testing, the specimens were mounted in an impact machine and subjected to crash-impact testing at 10 and 14 feet per second. The weight of the falling mass was 448 pounds. Two impact footprints were used: an 8- by 10-inch flat plate and a 1-inch-wide picture frame having outside dimensions of 8 by 10 inches. Six 20-kip load cells were mounted beneath the specimen to measure load. Two piezoelectric accelerometers, one at the center of the falling mass and one located 4 inches from the center, were used to measure deceleration. The output of the accelerometers and load cells was recorded on magnetic tape and used after the test to analyze the data. A schematic of the impact testing equipment is shown in Figure 8.

The results of the impact testing are presented in Figures 9 through 12. The failure mode for those specimens which demonstrated ductile behavior was characterized by an accordian-type effect with progressively larger wavelengths emanating from the apexes of both the upstanding and inverted tetrahedrons (see Figure 9). In general, the specimens without face sheets demonstrated slightly higher values of load than specimens with face sheets (see Figure 10). Similar trends can be seen in Figure 11 for the deceleration versus velocity. The specimens which failed in the ductile manner resulted in relatively low deceleration, as compared to those specimens which failed in a brittle manner. The Tetracore specimens impacted by the 8- by 10-inch plate which demonstrated ductile failures resulted in approximately a factor of 2 reduction over the aluminum skin/stringer

specimen impacted with the 8- by 10- by 1-inch picture frame. It should be noted that the Tetracore and aluminum specimens were not designed to the same strength/stiffness criteria and, thus, absolute comparisons are not possible. Venting (1/4-inch holes) had no discernible effect on the impact behavior.

Figure 12 presents typical load and deceleration time histories for both ductile and brittle failure modes. In the case of the brittle behavior, the specimens simply shattered on impact and the spikes indicate bottoming of the impact mass. The average compaction upon impact for the Tetracore specimens which failed in a ductile manner ranged from approximately 1.5 to 2.0 inches for the 10- and 14-fps impacts, respectively.

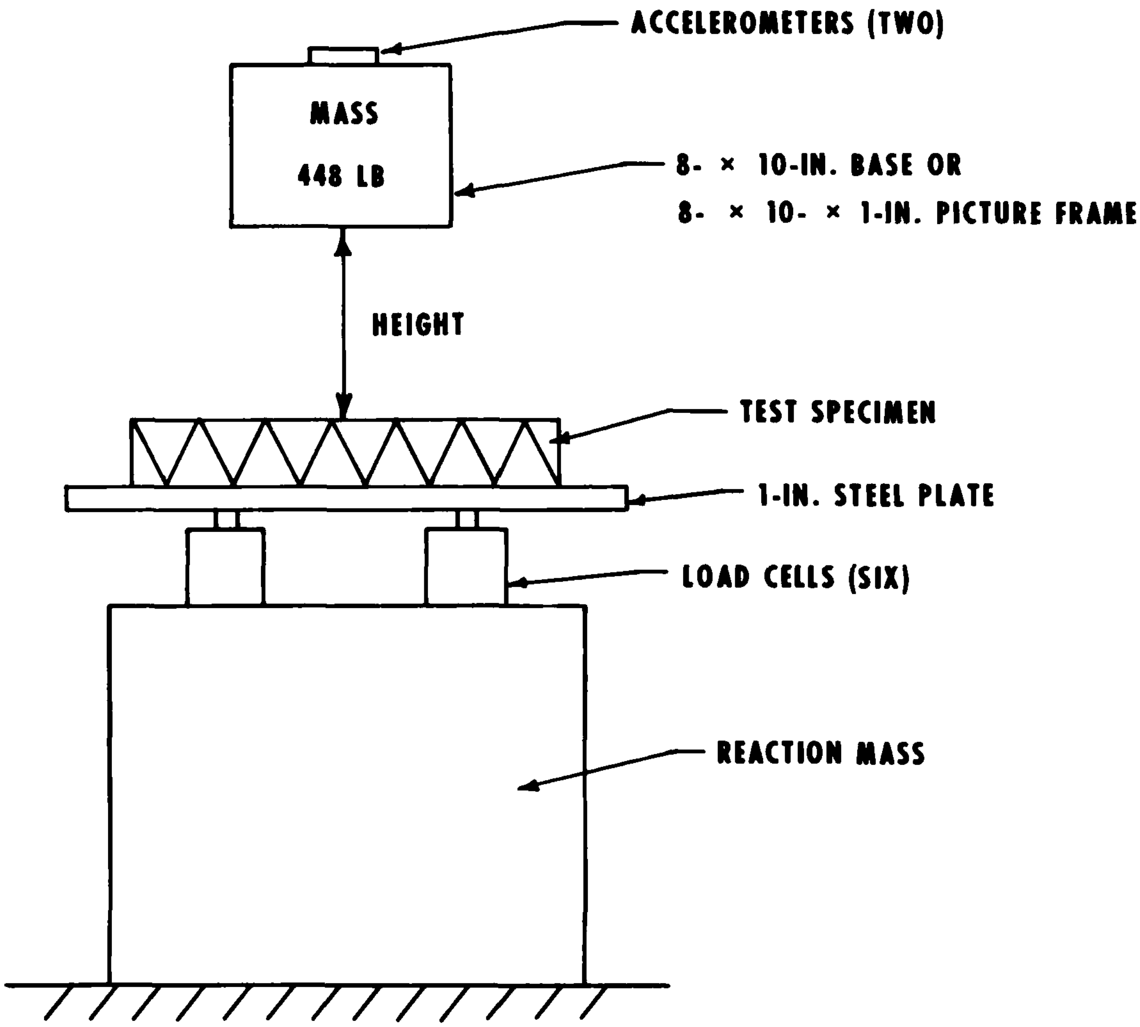

Figure 8. Test schematic.

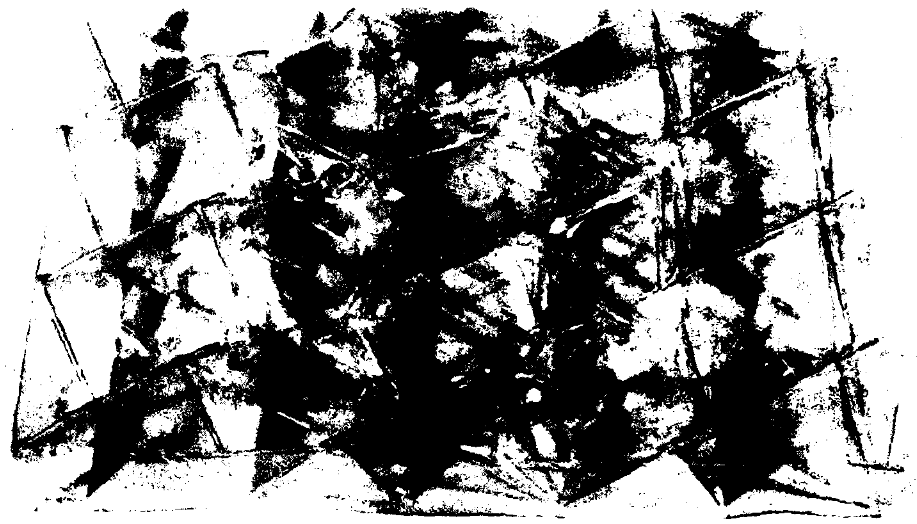

Figure 9. Failed Tetracore specimen.

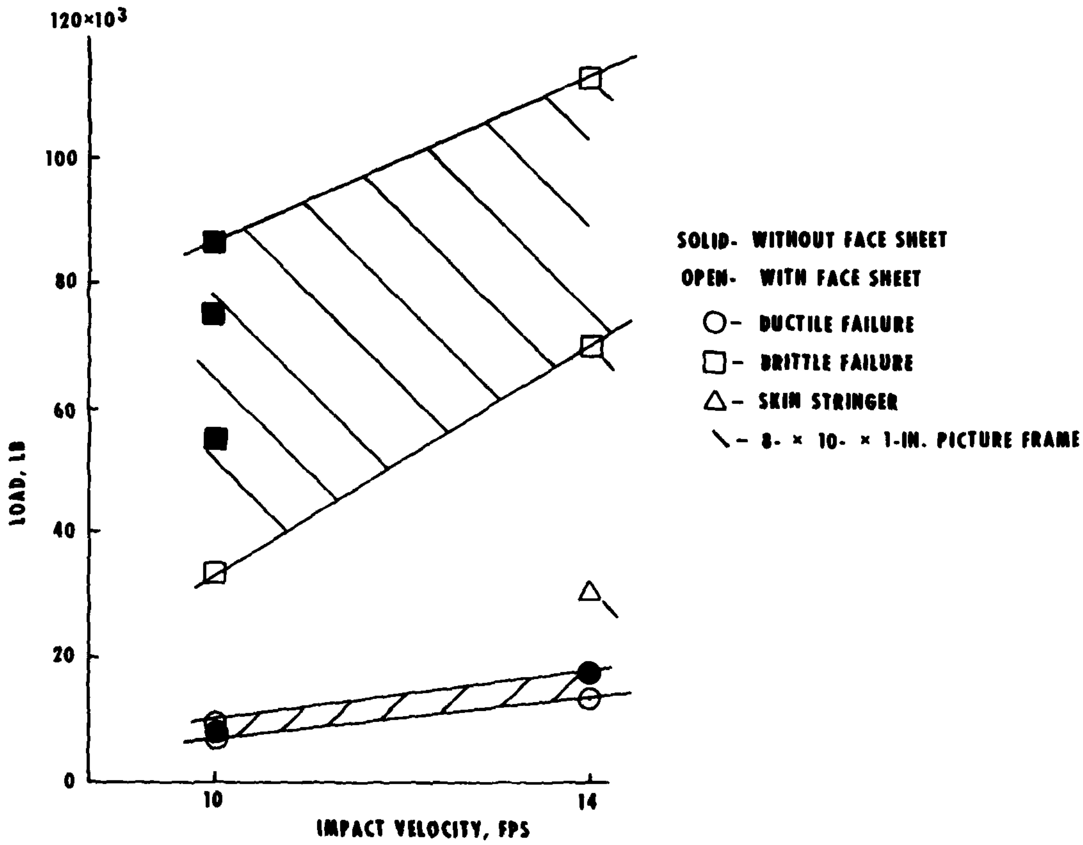

Figure 10. Effect of impact velocity on transmitted load.

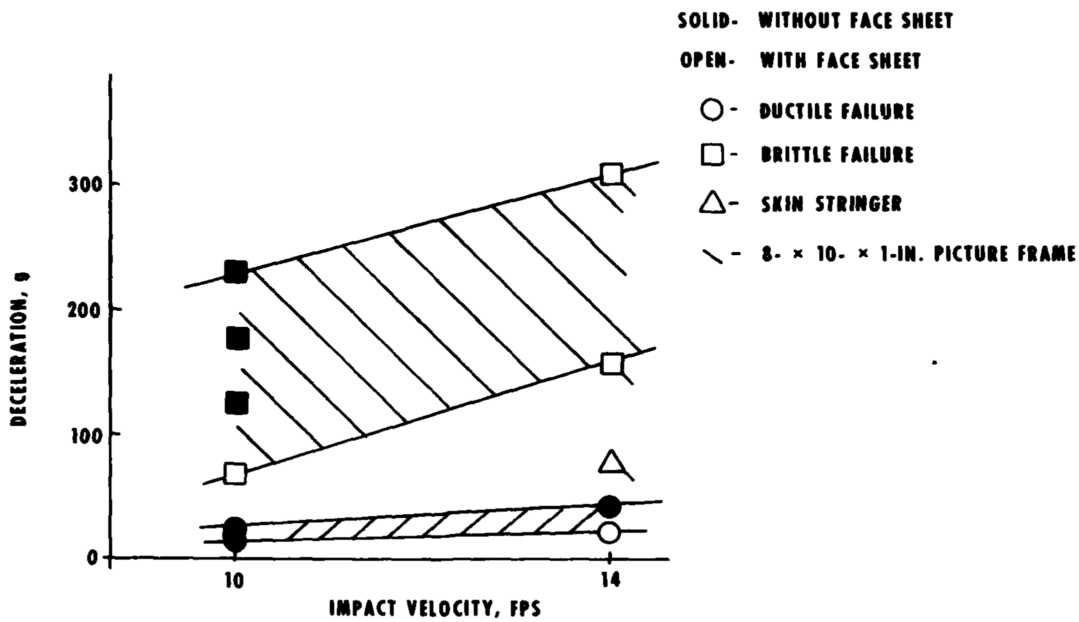

Figure 11. Effect of impact velocity on deceleration.

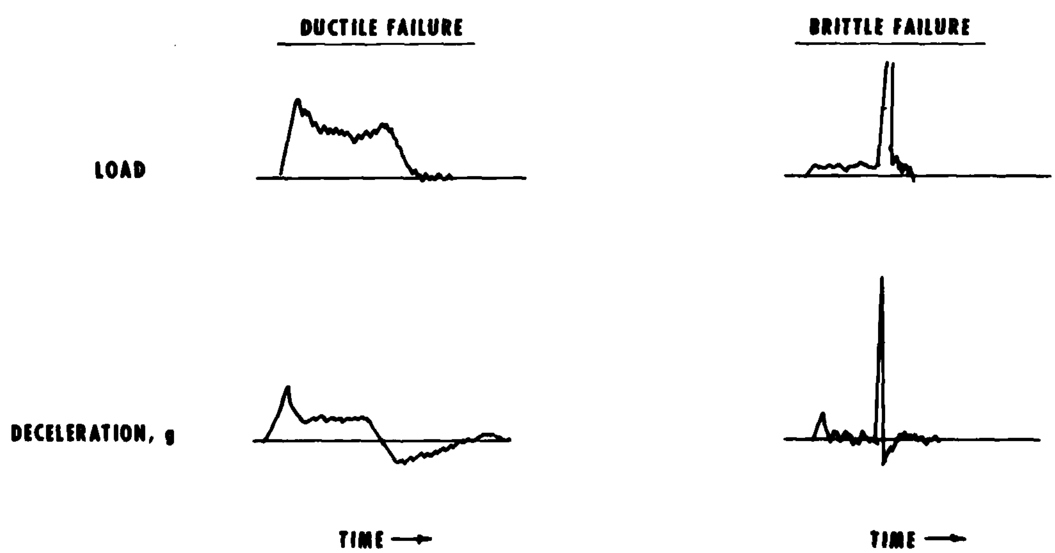

Figure 12. Typical load and deceleration time histories.

EFFECTS OF MEK

In general, the trends indicate that a soak in excess of approximately 4 hours is required before appreciable changes in static three-point bending deflection occur. At 6 hours, there is approximately a 50-percent increase in deflection (see Figure 13). Under impact loading the specimens subjected to the MEK soak failed in a ductile manner as compared to those specimens tested in the "as received" state which failed in a brittle manner (see Figure 14). It is evident that selection of materials which demonstrate a ductile failure mode, such as polyethylene, would produce desirable energy-absorbing characteristics. This desirable characteristic is primarily a function of the geometry of Tetracore and its associated accordian-type failure.

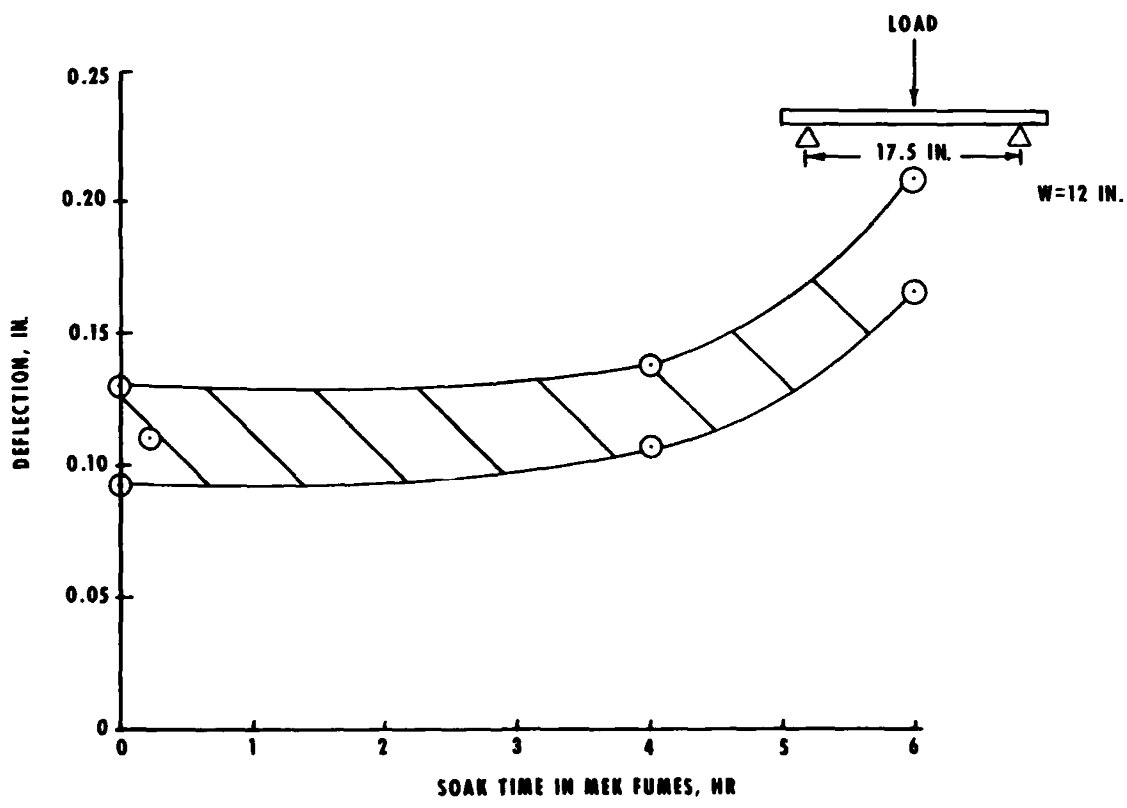

Figure 13. Effect of soak time on three-point bending behavior without face sheets.

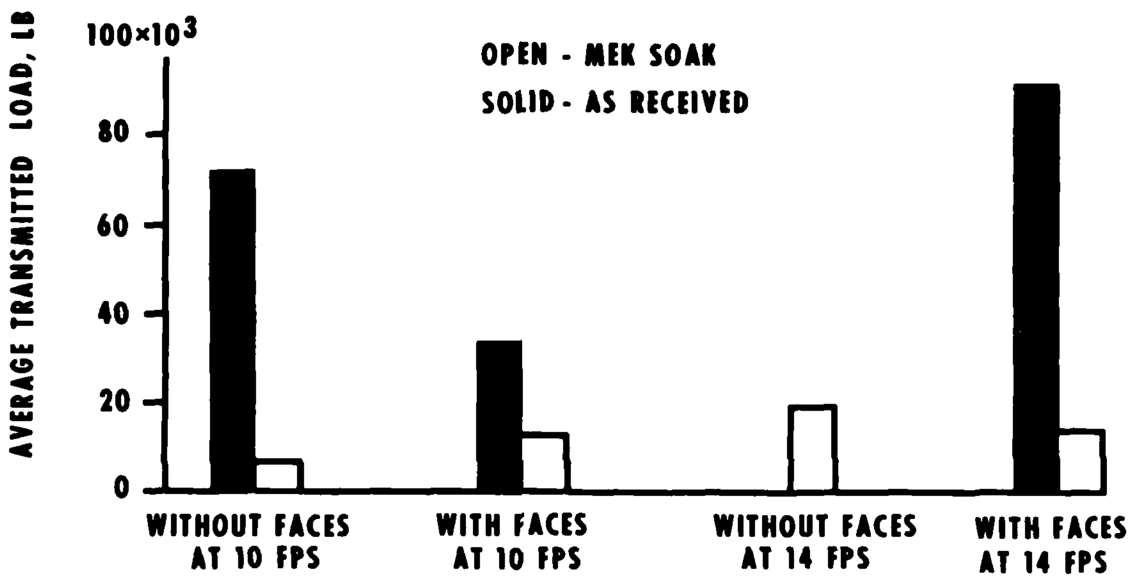

Figure 14. Effect of MEK soak on energy absorption.

TEST RESULTS

The results of both the static and impact tests are summarized in Tables 1 and 2.

TABLE 1. TEST RESULTS FOR CELLULOSE BUTYL-ACETATE TETRACORE SPECIMENS WITHOUT FACE SHEETS

Configuration	Wall thickness/ L x W, in.	Wt, gm	Soak time	Three-point deflection at 100 lb (17.5-in. span) before MEK soak	Three-point deflection at 100 lb (17.5-in. span) after MEK soak	Impact velocity, fps	Total impact load, lb	Peak deceleration, g	Failure mode
Halves dipped in Mek to effect bond	0.040/ 18.4 x 12.3	840	1 min	0.097	0.097	14.0	18,885	44.7	Ductile
Halves dipped in MEK to effect bond; cured 4 hr at 125°F	0.040/ 23.0 x 12.8	1038	1 min	0.130	0.130	9.7	7,831	17.2	Ductile
Spec immersed in MEK after bonding; spec highly distorted after soak	0.040/ 23.5 x 12.5	1015	5 min	0.110	0.110	10.1	6,689	14.3	Ductile
Spec subjected to MEK fumes	0.040/ 23.8 x 12.5	1015	4 hr	—	0.110	10.0	7,982	20.5	Ductile
Bonded with butyl-acetate	0.040/ 23.8 x 12.7	967	—	0.112	—	10.0	75,512	178.1	Brittle
Bonded with butyl-acetate; ¼-in. vents in tetrahedral faces	0.040/ 23.4 x 12.7	1034	—	0.103	—	9.9	54,980	128.1	Brittle
Bonded with butyl-acetate; cured 4 hr at 125°F	0.040/ 23.5 x 12.7	993	—	0.110	—	9.9	86,684	230.0	Brittle

TABLE 2. TEST RESULTS FOR CELLULOSE BUTYL-ACETATE TETRACORE SPECIMENS WITH ALUMINUM FACE SHEETS

Configuration	Wall thickness/ L x W, in.	Wt, gm	Soak time, hr	Three-point deflection at 100 lb (17.5-in. span) before MEK soak	Three-point deflection at 100 lb (17.5-in. span) after MEK soak		Impact velocity, fps	Total impact load, lb	Peak deceleration, g	Failure mode
					before face sheet applied	after face sheet applied				
Spec subjected to MEK fumes before 0.016 AL face sheet applied	0.040/ 23.5 x 12.6	1333	6	–	0.210	0.070	14.0	13,375	24.3	Ductile
Spec subjected to MEK fumes before 0.016 AL face sheet applied	0.040/ 23.5 x 11.8	1348	6	–	0.165	0.048	10.1	10,618	29.3	Ductile
Spec subjected to MEK fumes before 0.016 AL face sheet applied	0.040/ 23.8 x 12.4	1055	4	–	0.138	0.045	14.1	69,208*	159.8	Brittle
Bonded with butyl-acetate; 0.016-in. + 0.020 in. skins	0.030/ 24.8 x 12.8	1653	–	0.012	–	–	14.1	115,273*	310	Brittle
Bonded with butyl-acetate, 0.016 AL	0.040/ 21.0 x 12	1263	–	0.050	–	–	9.9	33,586*	68	Brittle
Metal skin/stringer spec	0.040/ 23.5 x 12.7	1318	–	0.005	–	–	14.0	31,000	78	Ductile

*Specimen impacted with 8-in. by 10-in. by 1-in. picture frame.

CONCLUSIONS

Based on the limited test results, wherein specimens compared were not all of the same design, the following conclusions have been made relative to the agreement with the math model and to the crash-impact energy-absorbing behavior of Tetracore:

1. The calculated three-point bending deflections[2] agree with the measured values for specimens with face sheets.

2. The measured deflections for specimens without face sheets fall considerably below the calculated values. This is attributed to the fact that the triangular elements in the outstanding faces (top and bottom) of the Tetracore specimen provided buckling stability to the legs of the Tetracore elements and carried some of the bending loads, thus, in effect, acting as partial face sheets.

3. The failure mode for those specimens which demonstrated ductile behavior was characterized by an accordian-type effect with progressively larger wavelengths emanating from the apexes of both the upstanding and inverted tetrahedrons. In general, this behavior produced significant reductions in decelerations as compared to the aluminum skin/stringer specimen.

4. Soaking specimens in MEK fumes had only minimal effects on static three-point bending deflection. However, the transformation from a brittle to a ductile failure mode as a result of the MEK soak has a significant beneficial effect on the transmitted load and associated decelerations during impact testing.

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